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A NEW TROPOPAUSE DEFINITION FROM SIMULTANEOUS OZONE-TEMPERATURE--ETC(U)
AUG 80 J M ROE, W H JASPERSON F19628-79-C-0098
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A NEW TROPOPAUSE DEFINITION FROM SIMULTANEOUS OZONE-TEMPERATURE PROFILES

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AD A091718

Scientific Report No. 1

August 1980

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AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AFB, MASSACHUSETTS 01731

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFGL-TR-80-0289	2. GOVT ACCESSION NO.: AD-A091 718
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): A NEW TROPOPAUSE DEFINITION FROM SIMULTANEOUS OZONE-TEMPERATURE PROFILES.	5. TYPE OF REPORT & PERIOD COVERED: Interim Technical Report No. 1, 1 July 1979-1 July 1980
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Jon M. Roe, W. H. Jasperson	8. CONTRACT OR GRANT NUMBER(s): F19628-79-C-0098 NEW
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Control Data Corporation, Research Division, P.O. Box 1249-C, Minneapolis, MN 55440 HQM251	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62101F 668705AV 05
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Geophysics Laboratory, Hanscom AFB, MA 07131, Monitor/R. E. Good/LKD	12. REPORT DATE: August 1980
	13. NUMBER OF PAGES: 14 16
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Tropopause definition
Temperature profile
Temperature lapse rate

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Historically, the tropopause has been defined arbitrarily in terms of particular features present in a temperature profile. This study suggests a modified definition which is consistent with the assumption that the tropopause is a boundary between the ozone rich air of the stratosphere and the ozone poor air of the troposphere.

Several hundred simultaneous temperature and ozone profiles from the middle 1960s and the latter 1970s were examined in order to arrive at a

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20. Abstract (Continued)

tropopause definition based on temperature and yet consistent with the ozone evidence. These data span a wide range of latitudes and seasons. Agreement between the conventional World Meteorological Organization (WMO) defined tropopause based on temperature lapse rate, and a tropopause defined subjectively on the basis of ozone gradients was found to be only 68%. However, a modification of the WMO tropopause definition, which relaxed the thickness criterion and considered the relative change in lapse rate from troposphere to stratosphere, produced a 95% agreement with the subjective tropopause based on ozone.

I. RESEARCH OBJECTIVES

The objective of the research effort is to re-evaluate the conventional definition of tropopause from the viewpoint of stratospheric-tropospheric exchange using simultaneous ozone-temperature profiles. In addition, a new objective definition of tropopause that is consistent with ozone evidence is to be formulated and applied to a ten-year global set of standard radiosonde temperature profiles to prepare a suitable climatology.

II. STATUS OF RESEARCH EFFORT

A. INTRODUCTION

The troposphere and stratosphere are two quite distinct layers of the atmosphere that can be very well defined by their large scale features. The tropopause is defined as the boundary separating the troposphere and the stratosphere. Ideally, this boundary is represented by an abrupt change in thermal stability. In reality, factors such as latitude, longitude, season, history of the air mass, and synoptic weather situation can make the determination of the tropopause height a difficult task.

Because of the differences in the average temperature structure between the troposphere and the stratosphere, the tropopause is most often defined in terms of an abrupt change in the temperature lapse rate. The World Meteorological Organization (WMO) has adopted a definition of tropopause based upon thermal stability that will be defined in a following section.

The assumption was made here that ozone is a good indicator of stratospheric air and may be used to identify the lower boundary of the stratosphere. In this study, several hundred ozonesondes that have simultaneous ozone-temperature profiles were examined. The WMO tropopause definition was modified to produce a new objective scheme of tropopause analysis that is more consistent with ozone.

The new objective scheme of tropopause analysis has been applied to a ten-year set of radiosonde data.

B. DATA

The simultaneous ozone-temperature profiles that were used for this study were taken from two sources. One was the AFCRL ozonesonde ascents from the mid-1960s and the other source was the World Data Center for Ozone in Toronto, Canada.

AFCRL ozonesondes present very fine vertical resolution for both ozone and temperature. Some of the soundings have points spaced about 150 m in the vertical while others have points spaced about 300 m apart. The spacing is fairly regular in the vertical because the atmospheric variables are given every 30 or 60 seconds. This results in approximately 100-200 levels reported from surface to 10 mb. The more standard ozonesondes obtained from Toronto usually report significant levels of ozone partial pressure along with mandatory levels. This results in approximately 50 levels reported from the surface up to 10 mb which is more detail than available in standard radiosonde temperature profiles.

From these data, 33 time sequences of at least daily ozonesondes were chosen from around the world. These time sequences last from about one week to one and one-half months. The requirement for at least daily ozonesondes narrowed the choices of time sequences substantially. It was necessary to have the best time resolution possible for analysis of ozone time sections so that synoptic scale disturbances in the ozone field could be resolved. The 33 time sequences are listed in Table 1 and contain a total of 495 ozonesondes, of which 474 were deemed complete enough for tropopause analysis.

One possible serious limitation to this effort is the rather small sample of simultaneous ozone-temperature profiles that are available in sequences of daily ozonesondes. Most ozonesondes are not taken daily. One would like to see in the future a much larger set of daily ozonesondes that cover more regions of the globe to see if the results of this investigation are truly general in nature.

C. ANALYSIS OF THE DATA

All 33 time sequences of simultaneous ozone-temperature profiles were plotted by computer. The ozone sequences were hand analyzed in the form of time sections of the ozone mass mixing ratio field. An example of an ozone time section is shown in Figure 3. The ozone mass mixing ratio field is plotted for one week of data. At concentrations of less than about 0.1 μg/g in the lower part of the figure, the field is not stratified vertically but is rather well mixed. All of the ozone time sections showed this tendency to go from well mixed to highly stratified when the ozone concentration reached a few tenths of a microgram per gram.

The temperature profiles for a given time sequence were carefully compared to the ozone field. It was found that whenever the ozone concentration had strong gradients in the vertical, the corresponding temperature profile showed a region of increased stability. This ozone increase usually occurred just above a large decrease in the temperature lapse rate, but at other times the stability change was more subtle.

The next step was to construct a set of subjectively determined "tropopauses" based on the evidence of large ozone gradients in the vertical. These tropopauses were selected at visible discontinuities in the temperature profile that were at or below the large ozone increases. This analysis produced a set of 474 subjectively defined tropopauses based on ozone evidence. A comparison was made between this set of tropopauses and the WMO defined tropopauses for the same temperature profiles. In 68% of the temperature profiles, the two tropopauses agreed while in the remaining 32% of the soundings the WMO defined tropopause was higher than the subjective ozone-based tropopause. The bias of WMO tropopauses toward higher heights suggested the possibility for the development of a modified tropopause-finding algorithm that was more consistent with ozone.

D. MODIFICATION OF THE WMO DEFINITION

Since the WMO definition of tropopause is central to the discussion in this study, its main points are given below.

1. The first tropopause (i.e., the conventional tropopause) is defined as the lowest level at which the lapse rate decreases to 2°C/km or less, and the average lapse rate from this level to any level within the next higher 2 km does not exceed 2°C/km.

2. A level otherwise satisfying the definition of tropopause but occurring at an altitude below that of the 500 mb level will not be designated a tropopause unless it is the only level satisfying the definition and the average lapse rate fails to exceed 3°C/km over at least 1 km in any higher layer.

Evidence from the previous section states that the WMO defined tropopause is too high 32% of the time in the experimental data set where ozone is considered. This is because both the WMO lapse rate and thickness criteria are too strict.

The first attempt at modification was simply to change the fixed criteria found in statement 1, above, from requiring a stability of 2°C/km over a depth of 2 km to requiring a stability of 2.8°C/km over a depth of 1 km. This change obviously relaxed the stability requirements in the WMO definition substantially. These new stability criteria were arrived at by carefully inspecting each test profile and are entirely empirical. This attempt at a modified WMO definition was compared with the subjective ozone-based tropopauses found earlier. In this case, 89% of the test profiles showed agreement as compared to 68% before the WMO definition was modified. This result lent credence to the idea that the WMO stability criteria must be, at least in general, relaxed.

The 11% of the profiles in disagreement with ozone evidence fell into two categories. Either they were borderline cases where a slight change of the criteria would bring them into agreement or they exhibited a large relative change in lapse rate that still was not stable enough absolutely to fit the stability criteria. In the second category were profiles where the troposphere contained large lapse rates (e.g., 8-10°C/km) and the abrupt change in lapse rate at the beginning of the ozone gradient was, for example, from 9°C/km to 4°C/km. Even though 4°C/km doesn't satisfy the tropopause stability criteria, there is a major change in character of the temperature profile at this level and the ozone concentration starts to increase rapidly at this level. The evidence from the temperature profiles suggested that a tropopause lapse rate criterion should be based on the relative change in lapse rate from troposphere to stratosphere rather than an absolute stability criterion such as $2^{o}C/km$. A simple linear relation between the two was deduced from the experimental temperature profiles

$$A = 0.629\gamma_T - 1.286$$

in which A is the tropopause temperature lapse rate criterion (replacing $2^{o}C/km$ in the WMO definition) that is calculated directly from the average lapse rate of the troposphere, γ_T. The average lapse rate of the troposphere is calculated from the 2 km deep layer immediately beneath a possible tropopause level. The basic ideas involved are diagrammed in Figures 1 and 2. Figure 1 is an example of a vertical temperature profile. Levels in a profile are successively tested for tropopause using the new definition. The temperature lapse rate that exists above a test level is designated by γ. The average lapse rate in the 2 km below the test level (i.e., the tropospheric lapse rate) is designated by γ_T. Figure 2 summarizes the lapse rate criteria for tropopause determination. The horizontal dashed line is the lapse rate criterion for the WMO definition. It is fixed at $2^{o}C/km$ no matter what the lapse rate of the troposphere might be. If the atmospheric lapse rate above the test level, γ, is equal to or less than $2^{o}C/km$, then a tropopause has been found. The solid line in Figure 2 is the lapse rate criterion developed in this study. It is fixed at $2.8^{o}C/km$ when the tropospheric lapse rate is less than $6.5^{o}C/km$ and it is fixed at $5^{o}C/km$ when the tropospheric lapse rate is greater than $10^{o}C/km$ (adiabatic). When the tropospheric lapse rate is between $6.5^{o}C/km$ and $10^{o}C/km$, the lapse rate criterion varies linearly between $2.8^{o}C/km$ and $5^{o}C/km$ as specified in the bottom equation. Thus, in this region, the relative change in lapse rate from troposphere to stratosphere is important in defining the tropopause. The thickness criterion for stability is kept fixed at 1 km as opposed to the 2 km required in the WMO definition.

With the above modifications, 95% agreement was achieved between the subjective ozone-based tropopauses and the new objective scheme. This is an improvement over the 68% agreement with the WMO defined tropopauses.

The new objective scheme is especially useful in the middle latitudes where synoptic scale waves are dominant. The tropopause is known to sharply subside within a vigorous tropospheric trough and, in fact, tends to fold itself in many cases. The intrusion of stratospheric air within these tropopause folds can be identified in temperature profiles by stable layers. This sharp subsidence of the tropopause is rarely detected by the WMO tropopause criteria but can be by the new scheme. An example of the difference between the new scheme and the WMO tropopause is presented in Figure 3. This figure is a weekly time section of ozone mass mixing ratio with the two tropopauses superimposed. The CDC tropopause is more consistent with the ozone data than the WMO tropopause, especially during a stratospheric intrusion.

E. TIME CONTINUITY CHECKING

When one deals with archived radiosondes, one can further improve and refine a tropopause finding algorithm by including some form of time continuity checking. The new tropopause definition is being used on archived radiosonde data and so time continuity checking has been incorporated. One must be very cautious in applying a time continuity check on sequential tropopause heights because they are known to vary over rather large altitude ranges on time scales of a day.

The development of the time continuity check was motivated by two main concerns. The first and most important concern is that any arbitrary numerical rule (e.g., lapse rate criterion) makes the tropopause algorithm more exacting and stringent than is appropriate for the quality of radiosonde temperature profiles. A rigid rule allows the tropopause to jump from one stable layer to another. This jumping can be caused by possible tropopause levels which alternately satisfy and fail the objective rules by small amounts. The time continuity check attempts to smooth out these arbitrary jumps. The second concern is for any high-frequency, high-amplitude variability that may be present and not real. The time continuity program is able to filter out narrow large spikes in a month of 12-hourly tropopause heights. Experiments with many months of archived data have shown good success in dealing with both possible problems.

The time continuity program scans a month of archived data looking for a tropopause height that is significantly different from both the previous sounding and the subsequent sounding. If the suspicious tropopause is higher than its neighbors in time, then that sounding is re-examined by slightly altering the new definition itself to allow the possibility of finding a lower tropopause that agrees better with time continuity. This can happen if a lower layer narrowly failed the new tropopause criteria when in fact it may be a tropopause. The new criteria are only slightly altered to accept these borderline cases. An analogous procedure is used for suspiciously low tropopauses also, but this time the new criteria are slightly altered to possibly choose a higher tropopause. If a different tropopause level is calculated due to time continuity checking, then it must be closer in height to both the previous and subsequent soundings to be accepted; otherwise, the original tropopause height remains.

After the month of tropopauses has been checked for time consistency, one final check is administered. All of the tropopause pressures are checked to detect extremely high tropopauses. A check similar to this has been used previously in connection with the conventional (WMO) tropopause. In that case, all tropopauses with pressures less than 30 millibars were rejected. The new scheme rejects all tropopauses with pressures less than 80 millibars, except in the tropics (0^{o}-25^{o} latitude) all year and in the subtropics (25^{o}-40^{o} latitude) in the summer half of the year where the ceiling is 50 millibars. No evidence of valid primary tropopauses above these limits has been encountered.

F. ARCHIVED RADIOSONDES

A very large data set of archived radiosondes is available for tropopause determination. This data set is global and contains over 1000 individual stations. The time period covered is from September 1963 through December 1973 and most stations have 00Z and 12Z twice-daily observations. The set consists of over 4.2 million individual radiosonde ascents that have been error checked previously. An additional stage of error detection for this data set has been incorporated into the automated computer program that finds tropopauses using the new definition. The automated scheme has completed the tropopause analysis of this ten-year data set.

Approximately 3.1 million primary tropopauses have been produced and recorded on magnetic tapes. Also, monthly means of pressure, temperature and height of the primary tropopause and the associated standard deviations have been calculated. On the order of one hundred thousand monthly means are printed on paper and recorded on magnetic tape. Formation of a climatology of this newly defined tropopause is currently underway.

A difficulty exists in applying this definition to the archived data set. Most of the archived radiosondes give temperature at significant levels and often one of these significant levels is a WMO coded tropopause. This results in a possible bias in the radiosonde data toward levels already picked as WMO tropopauses. A set of temperature profiles given at significant levels without prior assignment of a WMO tropopause level is preferable; however, the modified definition can and does pick lower significant levels as tropopauses. This problem is not so important when one remembers that the modified definition always chooses a tropopause at or below the WMO tropopause.

G. SUMMARY AND CONCLUSIONS

The location of the tropopause has been a subject of much investigation in the past 25 years. No one strict definition can be applied in all cases. Much of the time, there is a clear change in stability between the troposphere and stratosphere and a tropopause may be easily recognized. In some cases, it is very difficult to locate any such feature in a temperature profile. Often the problem under investigation dictates how the tropopause may be defined.

This research effort is concerned with the relationship between the tropopause and ozone. A modified WMO tropopause definition that is consistent with ozone evidence, yet based on temperature alone, has been developed.

A data set of 474 detailed simultaneous ozone-temperature profiles was used to develop the modified WMO tropopause definition. The modified definition yielded agreement 95% of the time with a set of ozone based subjectively determined tropopauses. The conventional WMO tropopause definition yielded agreement 68% of the time with the set of ozone tropopauses. The modified definition always produces tropopauses that are equal to or lower than the WMO defined tropopauses because the stability criteria are relaxed.

The greatest discrepancy between the two types of tropopause occurs in the middle latitudes where active synoptic scale waves are important. In this case, the modified definition produces substantially lower tropopauses than the WMO definition especially within active tropospheric troughs. The newly defined tropopauses are much more consistent with the location of the first large ozone increase in the vertical than are the WMO defined tropopauses.

The modified definition of tropopause has been written in the form of a computer program and applied to a ten-year global set of standard archived radiosondes. A climatology is in preparation.

III. LIST OF PUBLICATIONS

A paper is currently in preparation that parallels the material presented in this Technical Report. The title is "Re-evaluation of the Definition of Tropopause, Using Ozone." The authors are J. M. Roe and W. H. Jasperson, and it will probably be submitted to the Journal of Geophysical Research.

IV. PROFESSIONAL PERSONNEL

Dr. A. D. Belmont
Dr. W. H. Jasperson
Jon M. Roe

V. INTERACTIONS

The research discussed in this Technical Report was presented at the Spring Meeting of the American Geophysical Union held in Toronto, Ontario, Canada, during the week May 21-27, 1980.

VI. NEW DISCOVERIES, INVENTIONS OR PATENTS

None.

VII. OTHER STATEMENTS

More time was devoted to the definition phase of the study than was originally planned. This allowed the development of a much more reliable and accurate tropopause definition. Consequently, the phase of the contract dealing with the display of the climatology of the new tropopause has been delayed. Although all of the climatology has been calculated on magnetic tape, a suitable display of it has yet to be selected in consultation with the Technical Monitor. This will cause the ozone gradient task to be included in the second year. Discussions with the Technical Monitor will determine the priorities of the second year tasks.

Station	Lat.	Long.	Time
Tallahassee, Florida (FSU)	30.4°N	84.3°W	04/30-05/22/63
			01/11-01/27/65
			03/03-03/31/65
Albuquerque, New Mexico (UNM)	35.0°N	106.6°W	04/29-05/29/63
			01/06-01/27/65
			03/03-03/31/65
			12/01-12/23/65
Bedford, Massachusetts (Hanscom, AFB)	42.5°N	71.3°W	01/11-01/27/65
			03/03-03/31/65
			12/01-12/29/65
Seattle, Washington (UW)	47.4°N	122.3°W	03/03-03/19/65
			12/01-12/23/65
Goose Bay, Newfoundland	53.3°N	60.4°W	03/03-03/31/65
Fort Collins, Colorado (CSU)	40.6°N	105.1°W	04/29-05-22/63
Albrook Field, Canal Zone	9.0°N	79.6°W	04/30-05/29/63
Thule AFB, Greenland	76.5°N	68.8°W	05/01-05/29/63
Churchill, Manitoba	58.8°N	94.1°W	04/29-05/29/63
Yorkton, Saskatchewan	51.3°N	102.5°W	08/07-08/27/75
			08/07-08/31/76
			08/04-09/11/77
			08/10-08/24/78
Palestine, Texas	31.8°N	95.7°W	10/21-10/27/77
			12/01-12/04/77
			10/25-11/11/78
R/V AK. Shirshov (E. Ger.)	0°-12.7°N	68.0°-93.3°E	05/25-06/15/77
	0°-5.8°N	73.6°-80.1°E	07/20-07/30/77
	12.1°-17.2°N	90.9°-91.1°E	08/09-08/19/77
El Arenosillo, Spain	31.1°N	6.7°W	05/17-05/20/77
Cold Lake, Alberta	54.8°N	110.1°W	02/01-02/13/79
Fort Sherman, Canal Zone	9.4°N	79.9°W	07/16-07/31/77
Garmish Partenkirchen, W. Germany	47.5°N	11.1°E	01/31-02/27/79
Hohenpeissenberg, W. Germany	47.8°N	11.0°E	01/01-01/31/79
			02/02-02/28/79

Table 1. List of 33 ozonesonde time sequences. First 17 are from AFCRL and the last 16 are from Toronto World Data Center for Ozone.

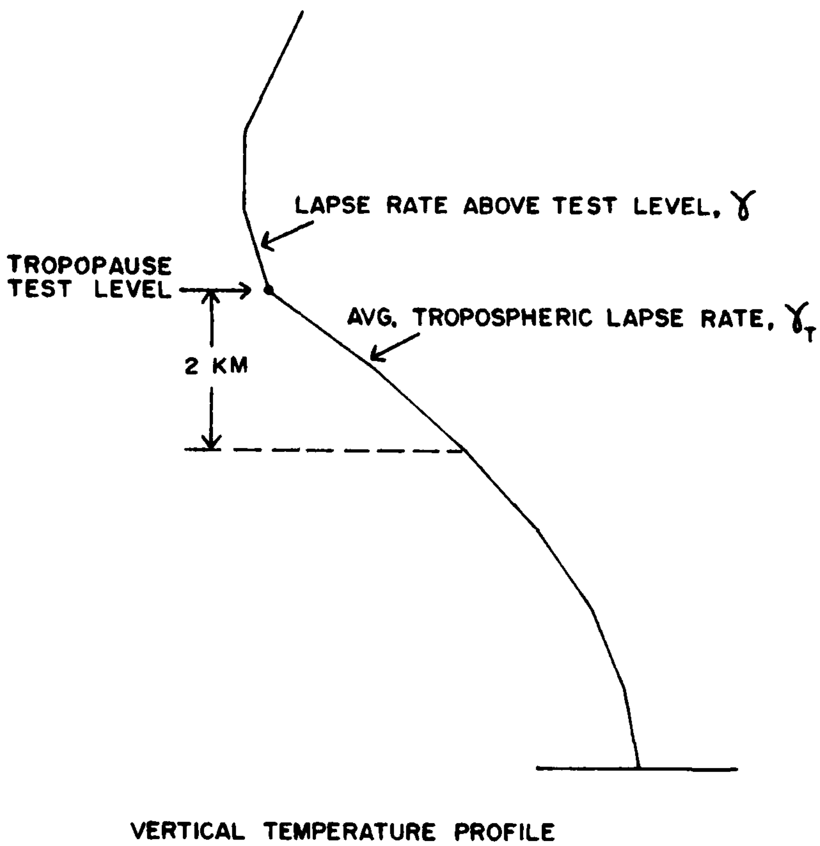
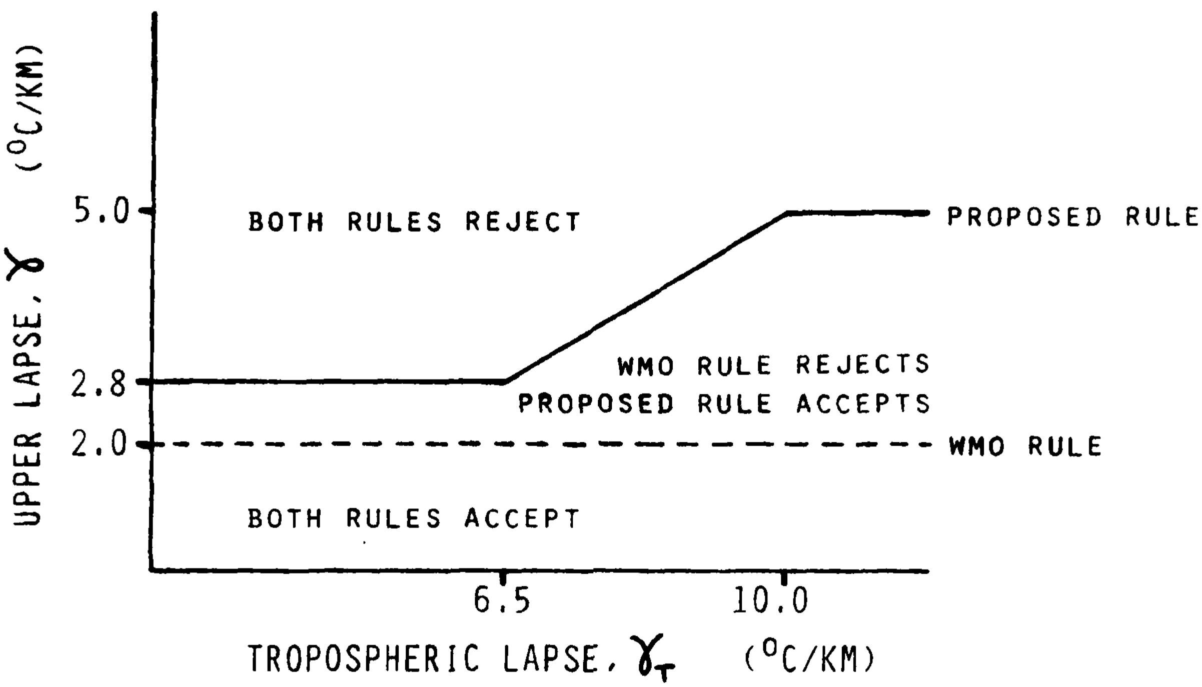


Figure 1. A temperature profile showing a level that is to be tested for tropopause using the criteria of Figure 2.

LAPSE RATE CRITERIA



PROPOSED RULE:

IF $\gamma > 5.0\ ^{o}C/KM$, REJECT

IF $\gamma < 2.0\ ^{o}C/KM$, ACCEPT

IF $2.8 \leq \gamma \leq 5.0$, ACCEPT IF:

$$\gamma \leq 0.6\gamma_T - 1.3$$

Figure 2. Graphical representation of tropopause lapse rate criteria showing regions of acceptance and rejection for the WMO and CDC tropopause (See text).

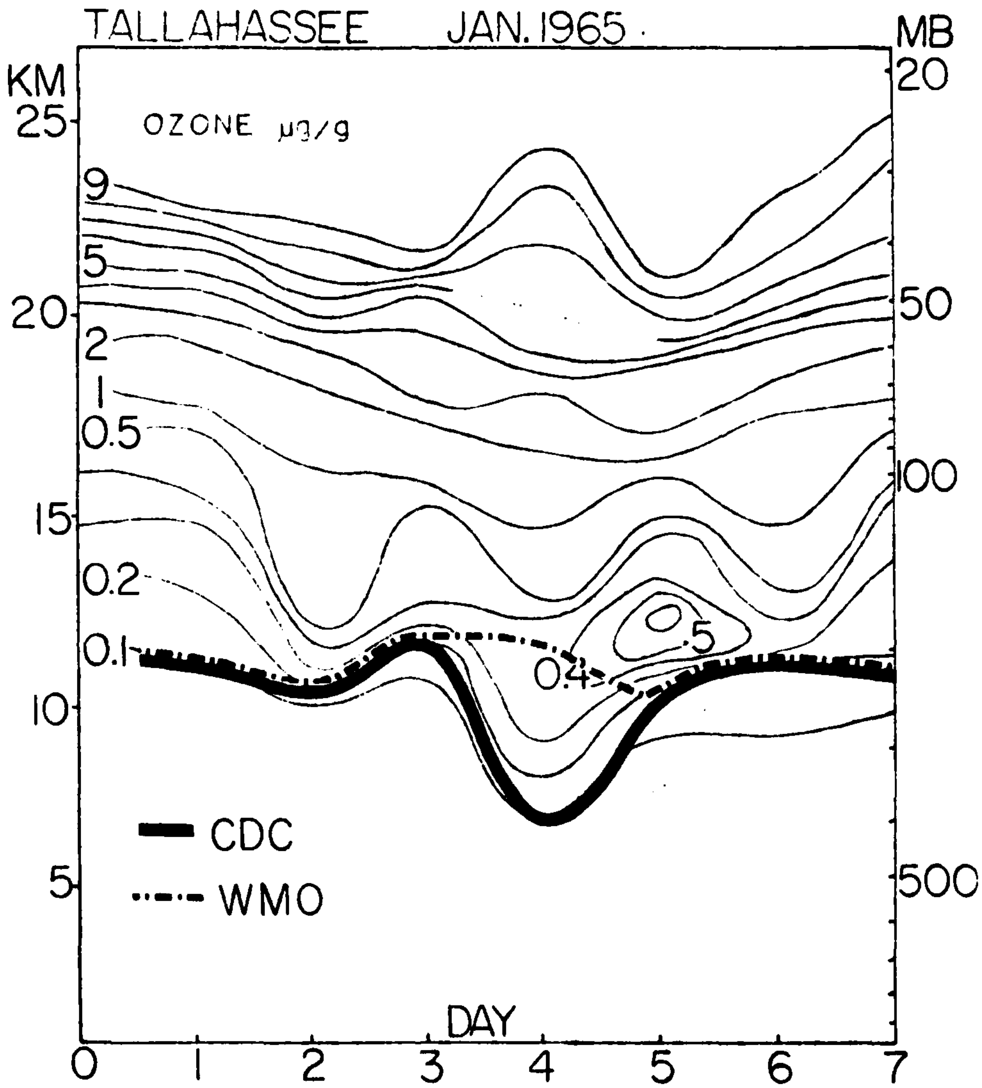


Figure 3. Time section of ozone concentration at Tallahassee, Florida for January 13-20, 1965. Ozone mass mixing ratio (μg/g) thin lines; WMO defined tropopause, heavy dashed line; CDC defined tropopause, heavy solid line.